The solar collector developed is characterized by high performance characteristics, in particular, low thermal resistance and low heat losses, and compactness, and it can be employed in the liquid and air setups.

NOTATION

a, hydraulic radius of a cell of the honeycombed fill, m; C, length of the condenser, m; E, length of the evaporator, m; F, angular coefficients referring to the solar radiation; $q(T_C)$, heat flux from the absorber of the collector, W/m^2; h_w, coefficient of heat exchange with the surrounding medium, W/(m^2•K); I, flux of solar radiation, W/m^2; k_a, coefficient of thermal conductivity of air, W/(m•K); L, height of the honeycombed fill, m; L_r, distance between the heat pipes, m; r, radius, m; R, thermal resistance, (m^2•K)/W; T, temperature, °K; T_n, conventional sky temperature, K; U_L, heat-loss factor W/(m^2•K); V, wind velocity, m/sec; $(\tau\alpha)$, reduced absorptivity; η_z, efficiency of the collector; σ, Stefan–Boltzman constant; ρ, total coefficient of reflection of thermal radiation; ρ^s, coefficient of specular reflection of thermal radiation; ρ^d, coefficient of diffuse reflection of thermal radiation; ρ_s, total coefficient of reflection of solar radiation; $\rho_s{}^d$, coefficient of diffuse reflection of solar radiation. Indices: c, condenser; e, evaporator; p, heat pipe; w, wick; v, vapor; f, liquid.

LITERATURE CITED

1. S. W. Chi, Heat Pipe Theory and Practice (A Source Book) Hemisphere Publ. (1976).
2. P. Dunn and D. A. Reay, Heat Pipes, Pergamon Press (1975).
3. C. K. Hsieh, "Design of a system using CPC collectors to collect solar energy and to produce industrial process steam," Report ANL-79-102, University of Florida (1979).
4. J. A. Duffie and W. A. Beckmann, Solar Energy Thermal Processes, Wiley, New York (1974).
5. J. Januszewski and W. Tomczak, Inzynieria Chemiczna i Procesowa, Wroclaw (1983), Vol. 4, No. 3, pp. 467-482.
6. J. Januszewski, S. Kajl, and F. Ruszel, Cieplownictwo, Ogrzewnictowo, Wentylacjz, 18, No. 3, 35-37 (1986).

MASS OF HYDROGEN LIBERATED IN STAINLESS STEEL HEAT PIPES WITH WATER DURING LENGTHY OPERATION

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UDC 536.248.2

The authors describe a method of calculating the amount of hydrogen liberated, based on experimental data of long-term performance tests of heat pipes.

Heat transfer in low-temperature stainless-steel heat pipes with water has a number of special features, compared with heat transfer in heat pipes where the materials of the wall, capillary-porous structure and heat-transfer agent are compatible with steam (e.g., copper–water). This stems primarily from the influence on the thermal technology characteristics of the heat pipe of the noncondensible gas liberated from the heat-transfer agent as a result of electrochemical corrosion of the metal in contact with the agent. The hydrogen formed gradually collects in the condensation zone, reducing the effective length and increasing the thermal resistance of the heat pipe. Up till now there has been practically no detailed study of the laws of gas liberation in stainless-steel heat pipes with water, aimed at determining the mass of hydrogen formed during long-term operation. For example, the investigations of [1] did not take into account the nonuniformity of hydrogen release with time, and were conducted over a short period of continuous operation of the heat pipe (3 months). The use of a formula proposed in [2] to calculate the mass of hydrogen liberated is difficult because there are no reliable data on the parameters appearing in the formula, parameters determined only experimentally (the activation energy, the overvoltage in the metal, the number of electrons taking part in the reaction, etc.), and whose number also varies with time.

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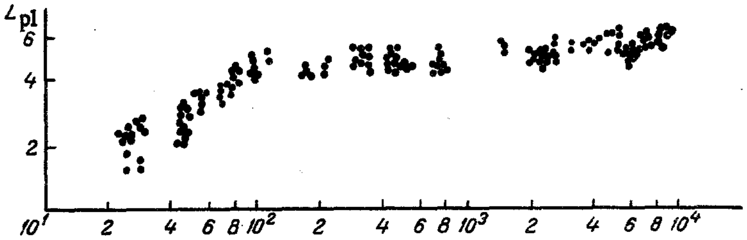

Fig. 1. Variation of the length L_{pl}, mm, of the plug of noncondensible gas as a function of time, h.

The aim of the present paper is to study gas liberation in a type 12Kh18N10T stainless-steel heat pipe, charged with water, to develop a method of calculating the mass of hydrogen liberated on the basis of experimental data on long-term operational tests of a heat pipe whose surface was protected using the technique proposed in [3], and to compare the experimental data with theory.

To study the influence of the various factors (working temperature, time, area of the corroding surface) on the laws of gas liberation, we created an experimental facility to let us investigate the operation of the heat pipe at different angles of inclination and to conduct long-term tests of heat pipes under continuous operation. The test object was a heat pipe of length 350 mm, diameter 12 mm, and wall thickness 1 mm (the lengths of the evaporation and condensation zones were 100 and 150 mm, respectively). All the pipes operated under steady conditions at a working temperature of 154°C, cooled by natural convection in a vertical position. The temperature of the surrounding medium was kept constant and controlled to an accuracy of one degree. Heat was supplied by electric heaters located on the entire surface of the evaporation zone. Temperature was measured along the pipe by copper—constantan thermocouples welded to the wall and inset in milled channels to a depth of 0.5 mm. To the base of the condensation zone of each pipe was welded a thin-walled capillary bushing into which a thermocouple was inserted and moved sequentially to determine the length and the temperature field of the plug of noncondensible gas. The heat transfer agent used was distilled deaerated water with pH = 6.85 and $c_{O_2} = 5 \cdot 10^{-8}$ kg/m³. The amount of the heat transfer agent charge was 15% of the internal volume of the pipe.

Analysis if the experimental data [4, 5] shows that the noncondensible gas, collecting in the condensation zone, forms a slug of which the shape and type of interface considerably influence the radial Reynolds Number (Re_r) and the heat flux supplied. Since the dimensions of the plug of noncondensible gas are restricted by the inside surface of the heat pipe and the vapor—gas interface, to determine the mass of hydrogen liberated we need to know the qualitative composition, the thermophysical properties and the plug length, besides the shape of the vapor—gas interface.

From the tests conducted in [3] it was observed that the size of the plug of noncondensible gas varied with time. While a sharp increase of plug length due to vigorous liberation of hydrogen was observed in the initial period of operation of the pipe, the growth of the plug slowed later because of reduced intensity of gas liberation. However, during the entire period of the long-term tests, no stabilization of plug size was noted, explained by the undamped nature of hydrogen liberation. The plug length was determined graphically on the basis of data on saturation temperature and temperature distribution in the plug of noncondensible gas. The saturation temperature was determined with the aid of thermocouples located in the vapor space of the evaporation zone and on the wall of the adiabatic zone. The results of the investigation showed that the plug length is described by a step function for the initial and the long-term periods of operation with t = const, S = const. The test data were reduced using the least squares method and are shown in Fig. 1.

In calculating the mass of gas liberated, we made the following assumptions: 1) all of the noncondensible gas is in the plug; 2) between the vapor and the gas there is a clear interface determined by the axial velocity component of the vapor flow; 3) the shape of the vapor—gas interface is a parabola; 4) the thermophysical properties of the heat transfer agent are determined at the saturation temperature when operating at the partial pressure of the vapor; 5) the pressure losses in the vapor channel are negligibly small; 6) the noncondensible gas obeys the equation of state of an ideal gas.

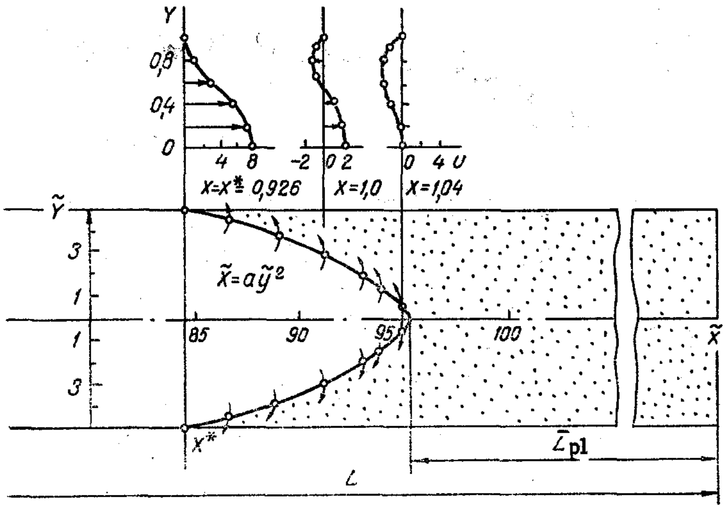

Fig. 2. Construction of the vapor–gas interface (τ = 2300 h) to determine the parabolic volume of the vapor–gas front ($\tilde{Y}$, radial coordinate, mm; $\tilde{X}$, axial coordinate, mm).

The method of calculating the mass of hydrogen liberated in the test heat pipes consists of the following steps:

1) find the axial velocity profile of the vapor flow for different sections of the active part of the condensation zone using the solution [6]:

$$U = 4B(1-X)(1-Y^2) + 2A_1X(1-4Y^2+3Y^4), \tag{1}$$

where $B = L_{act}/r$; $X = \tilde{X}/L_{act}$; $Y = \tilde{Y}/r$.

The quantity L_{act} was determined as $L_{act} = L - \bar{L}_{pl}$ because of the presence of vortex formation and smearing of the vapor–gas front along the heat pipe wall. The coefficient A_1 was calculated from the equation

$$0{,}1142A_1^2 - \left[0{,}267 - \frac{2{,}69}{\mathrm{Re}_r}\right] BA_1 - 0{,}133B^2 = 0, \tag{2}$$

where $\mathrm{Re}_r = \mathrm{Re}_a/4\ r/z$ [7].

The value of z was assumed equal to the mean plug length $\bar{L}_{pl}$ and was determined as

$$\bar{L}_{pl} = a_1\tau^{b_1},\ 0 \leqslant \tau \leqslant 150; \tag{3}$$

$$\bar{L}_{pl} = a_2\tau^{b_2},\ 150 \leqslant \tau \leqslant \infty, \tag{4}$$

where $a_1 = 1.54$; $a_2 = 30.44$; $b_1 = 0.73$; $b_2 = 0.078$ are coefficients obtained empirically on the basis of the test data of [3] and characterizing the nonuniformity of gas liberation with time;

2) determine the coordinates of the start of reverse flows for different sections of the active part of the condensation zone as r varies from 5 mm to 0 (Fig. 2);

3) construct the vapor–gas interface with the aid of points of inflection on the axial velocity profiles of the vapor flow and determine the paramolic volume of the vapor–gas front (Fig. 2);

4) determine the volume of the plug of noncondensible gas

$$V = V_{cyl} - V_{vgf} = \frac{\pi d^2}{4} X^* - \pi \int_0^{\tilde{X}} \tilde{Y}^2 d\tilde{X}; \tag{5}$$

5) calculate the mass of hydrogen liberated using the gas constant equation. Here we take into account the presence in the plug of noncondensible gas of vapor with a density corresponding to the saturation pressure of water at the mean temperature of the plug and of residual nitrogen partially retained on the inside surface after degassing of the pipe and liberated at the working temperature as the pipes operate.

After the tests we carried out a gas analysis of the plugs of noncondensible gas formed. Figure 3 shows the spectrum of noncondensible gas liberated in a heat pipe operated continu-

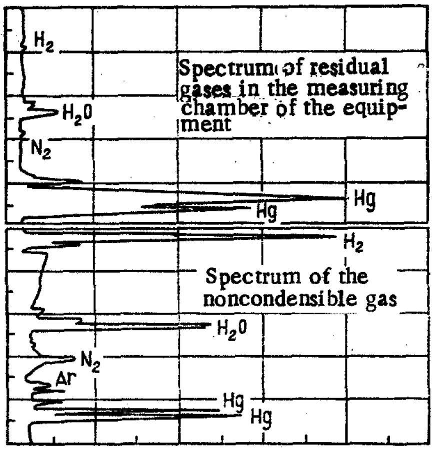

Fig. 3. Spectrum of the plug of noncondensible gas in a type 12Khl8N10T stainless steel heat pipe with water (τ = 2300 h).

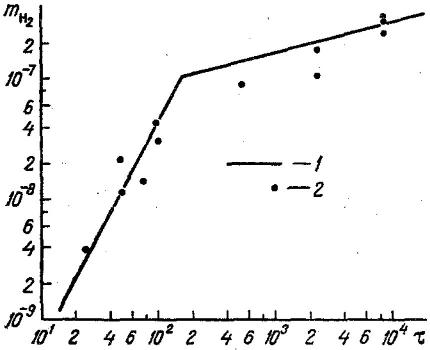

Fig. 4. Mass of hydrogen liberated, m_{H_2}, kg, as a function of the time of continuous operation τ, h: 1) theory; 2) test data.

ously for 2300 h, obtained on an equipment for qualitative and quantitative determination of the components of plugs of noncondensible gas. As can be seen from Fig. 3, the basic components of the plugs of noncondensible gas are hydrogen, nitrogen, and water. The amount of argon introduced into the heat pipe when the charging stem was sealed off by argon-arc welding is negligibly small in comparison with the components calculated above, and can be neglected. The mercury peaks are the main background of the measuring chamber, due to the vacuum pumps.

After this method was used to calculate the amount of hydrogen liberated in 15 heat pipes operated continuously for different time periods, we constructed the dependence $m_{H_2} = f(\tau)$, with t = const and S = const. Figure 4 shows the results of these investigations, in which we observe good agreement between values obtained by experiment and theory. The gas analysis data also confirm the nonuniformity of hydrogen liberation in the initial and long-term periods of operation, explained by the complex nature of the corrosion process occurring in a closed system such as the heat pipe.

Thus, with the method of calculation described one can determine the mass of hydrogen liberated in a type 12Khl8N10T stainless steel heat pipe charged with water, for various times of continuous operation.

It was discovered from the investigations that the gradual buildup of hydrogen causes an increase of the length of the plug of noncondensible gas, which in turn reduces the effective surface area of the condensation zone and decreases the heat transmission characteristics of the heat pipe. Therefore, knowing the laws of gas liberation and of variation of the size of the plug of noncondensible gas as a function of the working temperature, the operating time, and the geometric characteristics of the heat pipe (the area of the corroding surface, the inside diameter), without preliminary variation of the thermophysical properties of the heat-transfer agent, we can accelerate operational tests and define periods of optimal duration of use of heat pipes with a given combination of materials of the wall, capillary-porous structure and heat-transfer agent, under constant operating conditions and under variable conditions.

NOTATION

pH, hydrogen indicator; c_{O_2}, concentration of oxygen in the heat-transfer agent; Re_r, radial Reynolds number; Re_a, axial Reynolds number; U, dimensionless axial velocity component of the vapor flow; B, geometric parameter; C, dimensionless axial coordinate; Y, dimensionless radial component; $\tilde{X}$, axial coordinate; $\tilde{Y}$, radial coordinate; d, r, inside diameter and radius of the heat pipe, respectively; L, length of the condensation zone; L_p, length of the plug of noncondensible gas; L_{act}, length of the active part of the condensation zone; τ, time; V, volume; X*, coordinate of the start of reverse flow; S, area of the corroding surface; t, temperature; m_{H_2}, mass of hydrogen liberated. Subscripts: cyl, cylinder; vgf, vapor—gas front.

LITERATURE CITED

1. I. G. Shekriladze and I. G. Avalishvili, Promysh. Teplotekh., 4, No. 2, 25-29 (1982).
2. V. V. Gil, E. N. Minkovich, and A. D. Shnyrev, Inzh.-Fiz. Zh., 31, No. 4, 594-600 (1976).
3. M. G. Semena, V. F. Panasenko, and A. I. Rudenko, Izv. Vyssh. Uchebn. Zaved., Energ., No. 7, 79-82 (1986).
4. A. A. Parfent'eva, V. D. Portnov, V. Ya. Sasin, and Yu. N. Dominitskii, Tr. Mosk. Energ. Inst., No. 448, 44-50 (1980).
5. V. V. Galaktionov, A. A. Parafent'eva, V. D. Portnov, and V. Ya. Sasin, Inzh.-Fiz. Zh., 42, No. 3, 387-392 (1982).
6. A. A. Parfent'eva and V. D. Portnov, Inzh.-Fiz. Zh., 47, No. 3, 427-432 (1984).
7. P. D. Dan and D. A. Rei, Heat Pipes [Russian translation], Moscow (1979).

RATE OF SURFACING OF A GAS PLUG IN ANNULAR AND RECTANGULAR VERTICAL CHANNELS

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UDC 532.529

Relations are proposed for the limiting surfacing velocities of plugs used within a broad range of geometric parameters.

When constructing the diagram depicting two-phase flow regimes for calculation of plug flow in vertical channels of different shapes, it is necessary to know the rate of surfacing of a single gas plug in a capped pipe or the rate of descent of fluid at which the plug is suspended in the channel.

The limiting (steady-state) surfacing velocity of a gas plug is determined by the hydrodynamics in the flow of the fluid around the frontal part and does not depend on the length of the plug. When inertial and buoyancy forces predominate, this velocity is determined by the relation [1]:

$$\mathrm{Fr}(l) = \frac{U_\infty \sqrt{\rho'}}{\sqrt{g(\rho' - \rho'')l}} = A_1, \tag{1}$$

where l is a characteristic linear dimension of the channel, equal to the diameter for a pipe, the external diameter for an annular channel, the diameter of the shell for a rod assembly, and the width (of the larger side) for a rectangular channel; A_1 is an empirical coefficient determined from Fig. 1a.

The data in [1] for A_1 in rectangular channels was used in [2] to propose the linear approximation

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